Axion dark matter from frictional misalignment

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1 Overview of the misalignment mechanism

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Misalignment Mechanism

Assuming a pre-inflationary scenario for the scale of Peccei-Quinn breaking the value of the axion after inflation would be homogeneous $\frac{a_i}{f} \equiv \theta_i = \mathcal{O}(1)$
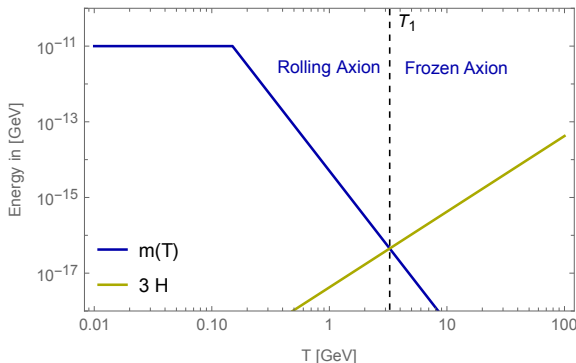and follows the eom

$$\ddot{\theta} + 3H\dot{\theta} + m(T)^2 \sin(\theta) = 0 \tag{1}$$

At early times $3H \gg m(T)$ the axion is frozen at it's initial value

$$\theta(T) = \theta_i \tag{2}$$

At around $3H \sim m(T)$ the axion is released starts oscillating around the bottom of the potential.
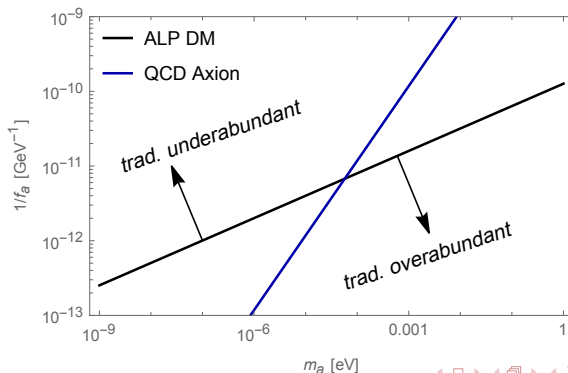
Misalignment Mechanism

At late times the axion behaves as dark matter

$$A = \frac{a^3 \rho_a}{m(T)} = \mathrm{ct} \rightarrow \rho_a \propto a^{-3} \tag{3}$$

Misalignment Mechanism

Axion dark matter abundance

$$\frac{\rho_{a,0}}{\rho_{\rm DM}} \simeq 28 \sqrt{\frac{m_a}{\rm eV}} \sqrt{\frac{m_a}{m_{\rm osc}}} \left(\frac{\theta_i\, f_a}{10^{12}\,{\rm GeV}} \right)^2 \mathcal{F}(T_{\rm osc}) \qquad (4)$$

Axions in a thermal bath

We assume an axion coupled to a dark non-Abelian gauge field which forms a thermal bath of temperature T'

$$\mathcal{L} \supset \frac{\alpha}{8\pi} \theta F_{\mu\nu}^b \widetilde{F}^{b\mu\nu}, \tag{5}$$

The effective EOMs for the axion background and gauge field are

$$\ddot{\theta}_a + \left[3H + \Upsilon(T')\right] \dot{\theta}_a = -\frac{1}{f_a^2} V'(\theta_a), \tag{6}$$

$$\dot{\rho}_{\mathrm{dr}} + 4H\rho_{\mathrm{dr}} = f_a^2 \, \Upsilon(T') \, \dot{\theta}_a^{\,2} \tag{7}$$

Properties of the thermal bath

Friction coefficient for $\alpha < 0.1$

$$\Upsilon(T') = \frac{\Gamma_{\rm sph}}{2T'f_a^2} \simeq 1.8 \times \frac{N_c^2 - 1}{N_c^2} \frac{(N_c\alpha)^5 \, T'^3}{2f_a^2} \tag{8}$$

by McLerran et al. Recently revived by Berghaus et al and applied to inflation, dark energy etc.
Running of the coupling is important

$$\alpha\left(T'\right) = \frac{4\pi}{\bar{b}_0 N_c} \frac{1}{\ln\left(T'^2/\Lambda^2\right)} \tag{9}$$

where $\bar{b}_0 = \frac{11}{3}$ for confinement or $\frac{10}{3}$ spontaneous symmetry breaking.

Properties of the thermal bath

$\rho_X \equiv$ energy of dark gauge field and its decay byproducts

$$\Delta N_{\mathrm{eff}} = \frac{8}{7} \left(\frac{11}{4} \right)^{\frac{4}{3}} \frac{\rho_X}{\rho_\gamma} \bigg|_{T=T_{\mathrm{rec}}} < 0.3 \text{ at } 95\% \text{C.L.} \qquad (10)$$

We define $\xi \equiv \frac{T_0'}{T_0}$

$$\Delta N_{\mathrm{eff}} = 0.016 \times n^{-1/3} \left(2N_c^2 - 2 \right)^{4/3} \xi^4, \qquad (11)$$

For $SU(3)$ we get $\xi < 0.86$

Properties of the thermal bath

The temperature of the dark thermal bath can be related to the standard model temperature through their respective entropy conservation.

$$T' = \xi \left(\frac{g_{\mathrm{s,SM}}(T) \, g'_{\mathrm{s}}(T'_0)}{g_{\mathrm{s,SM}}(T_0) \, g'_{\mathrm{s}}(T')} \right)^{1/3} T \tag{12}$$

Motion of the axion at early times

For $m(T) \equiv m_0 \left(\frac{\Lambda}{T}\right)^\beta$, if $3H \gg \Upsilon(T')$

$$\theta_a(T) \simeq \theta_i \mathrm{e}^{-\frac{m_a(T)^2}{6(2+\beta)H(T)^2}} , \tag{13}$$

whereas if $\Upsilon(T') \gg 3H$

$$\theta_a(T) \simeq \theta_i \mathrm{e}^{-\frac{m_a(T)^2}{(5+2\beta)\Upsilon(T')H(T)}} , \tag{14}$$

The onset of rolling is given by

$$m_a(T_{\mathrm{osc}}) \simeq \begin{cases} 4\,H(T_{\mathrm{osc}}) & , \ 3H > \Upsilon \\ \dfrac{10\Upsilon(T'_{\mathrm{osc}})\,H(T_{\mathrm{osc}})}{m_a(T_{\mathrm{osc}})} & , \ 3H < \Upsilon \end{cases} \tag{15}$$

Motion of the axion at late times

We derive a new adiabatic invariant for generic friction coefficient $\Gamma(T)$

$$A = \frac{\rho_\theta(t)}{\omega(t)} \exp\left[\int^t d\tilde{t}\, \Gamma(\tilde{t})\right] = \text{const}, \qquad (16)$$

Which recreates the correct result when $\Gamma(T) = 3H(T)$

$$A = \frac{\rho_\theta(T)}{m_a(T)} \exp\left[\int_{t_{\text{osc}}}^t d\tilde{t}\, 3H(\tilde{t})\right] = \frac{\rho_\theta a^3}{m_a} = \text{const}. \qquad (17)$$

and yields a new result when one considers both Hubble and thermal friction

$$A_{\text{fr}} = \frac{\rho_\theta(T)\, a^3(T)}{m_a(T)} \exp\left[\int^t d\tilde{t}\, \Upsilon(\tilde{t})\right] = \text{const}. \qquad (18)$$

DM abundance in the presence of friction

$$\frac{\rho_{a,0}}{\rho_{\mathrm{DM}}} \simeq \underbrace{28 \sqrt{\frac{m_a}{\mathrm{eV}}} \sqrt{\frac{m_a}{m_{\mathrm{osc}}}} \left(\frac{\theta_i \, f_a}{10^{12} \, \mathrm{GeV}} \right)^2 \mathcal{F}}_{\text{standard result}} \underbrace{\mathrm{e}^{-D}}_{\text{suppression}} \underbrace{\left(\frac{m_{\mathrm{osc}}}{4 \, H_{\mathrm{osc}}} \right)^{3/2}}_{\text{enhancement}}$$

(19)

where

$$D \simeq 6.3 \left(\frac{10^8 \, \mathrm{Gev}}{f_a} \right)^2 \left(\frac{\Lambda}{150 \, \mathrm{MeV}} \right)$$
$$\times \left[\frac{\tau^3 + \tau^2 + 2\tau + 6}{\tau^4} \, e^{\tau} - \mathrm{Ei} \left(\tau \right) \right]_{\tau_{\mathrm{osc}}}^{\tau_{\mathrm{end}}}$$

(20)

and $\tau \equiv \ln \left(\frac{T'}{\Lambda} \right)$
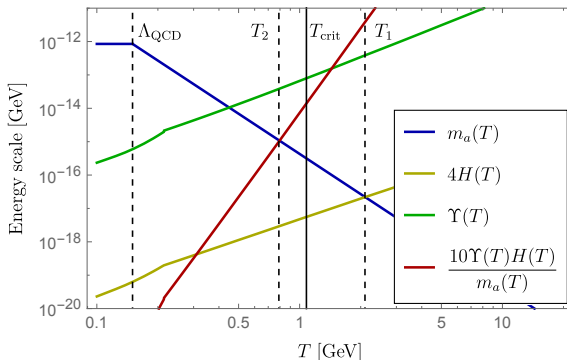
Basic mechanism

Figure 1: Example for the QCD axion

Minimal ALP scenario

We assume a single gauge group that gives rise to the mass through instanton effects and friction through sphaleron transitions. In that case $m_0 = \frac{\Lambda^2}{f_a}$
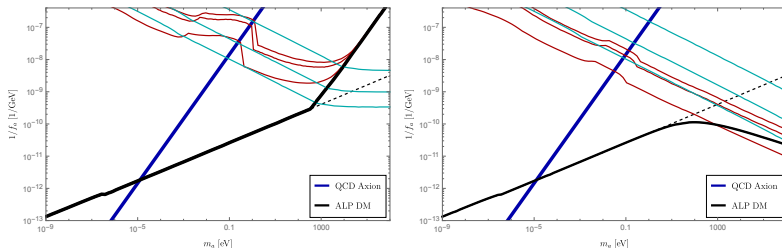

Figure 2: Left panel for $\alpha_{\mathrm{thr}} = 0.2$ and right panel for $\alpha_{\mathrm{thr}} = 0.4$

Overview of the misalignment mechanism   Axions in a pure Yang-Mills thermal bath   DM from frictional misalignment   Conclusions

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ALP coupled to two gauge groups

The model under consideration is

$$\mathcal{L}_{\mathrm{int}} = \frac{\alpha_G}{8\pi}\theta_a G_{\mu\nu}^b \widetilde{G}^{b\mu\nu} + \lambda \frac{\alpha}{8\pi}\theta_a F_{\mu\nu}^b \widetilde{F}^{b\mu\nu}\,, \qquad (21)$$

In this case $m_0 = \frac{\Lambda_G^2}{f_a}$, we define the enhancement parameter

$$\lambda \equiv \text{enhancement parameter} \qquad (22)$$

which we assume may be very large. Such largeness can be justified by alignment (Kim et al) or clockwork mechanism (Kaplan et al) in which case $\lambda = 3^N$.

ALP coupled to two gauge groups (underabundant case)

Condition for opening the underabundant regime:

$$T_2 \leq T_{\mathrm{crit}} \tag{23}$$

where $T_{\mathrm{crit}} \simeq 21.6 \, \mathrm{GeV} \left(\frac{m_a f_a}{\mathrm{GeV}^2} \right)^{4/7} \frac{\mathcal{F}^{1/7}}{g_{\rho,\mathrm{SM}}(T_{\mathrm{crit}})^{3/28}}$

Simplifies to

$$\frac{\mathcal{F}_a \left(\frac{m_a f_a}{17.0 \, \mathrm{GeV}^2} \right)^{10/7} \lambda^2}{\left[1 + 0.17 \left(\ln \left[\mathcal{F}_b \left(\frac{m_a f_a}{\mathrm{GeV}^2} \right)^{1/7} \right] + \ln \left[\Lambda_G^2 / \Lambda^2 \right] \right) \right]^5} > 1 \tag{24}$$

ALP coupled to two gauge groups (overabundant case)

- We simply demand that the axion dilutes sufficiently enough after it starts to roll so that its abundance matches the observed one.

- The minimum value of λ in this case is when the friction is the minimum possible over the longest possible time
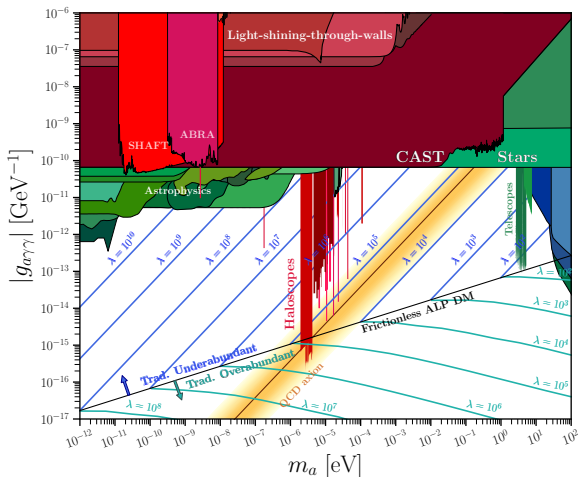
ALP DM parameter space

Figure 3: Minimum enhancement parameter λ for ALP DM

What about the QCD axion?

The same results apply for the QCD axion with two important differences

- Our conclusions require a small correction due to the presence of light degrees of freedom charged under QCD.

  ~~$m_a^{\mathrm{QCD}} f_a = \Lambda_{\mathrm{QCD}}^2$~~ instead

$$m_a^{\mathrm{QCD}} f_a = m_\pi f_\pi \frac{\sqrt{z}}{1+z}, \quad \text{where } z \equiv \frac{m_u}{m_d} \tag{25}$$

- The only possible fate of the hidden sector is spontaneous breaking so that the axion potential is not affected and the strong CP problem is solved.

Conclusions

- We call this mechanism "Frictional misalignment". We hope to add it to a short list of other modifications of the standard mechanism such as "Kinetic misalignment" Co et al, "Trapped misalignment" Di Luzio et al etc.

- It can open up both the traditional over and underabundant regimes.

- Most of the parameter space requires the clockwork mechanism to justify the large scale hierarchy.

- It mostly evades constraints from axion fragmentation.

- Works for the QCD axion.

- Alters the picture in the minimal model for axion masses greater than 10^2 eV

Thank You